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Study of the two-stage gasification process of pulverized coal at the hydrodynamic flow separation

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Abstract. The paper presents a numerical study of advanced two-stage gasifier with a combined countercurrent and concurrent flow pattern and dry fuel feed system EAGLE. The Kuznetsk coal was used as a fuel for the gasifier under study. We have conducted studies on the influence of the inclination angle of the upper burners in horizontal and vertical planes, and the amount of steam supplied, on heat and mass transfer processes in the chamber as well as on the composition of coal-derived gases. It is shown that the increase in the inclination angle of the upper burners in the horizontal plane allows intensifying the process of two-stage gasification and makes it possible decreasing the height of the chamber without sacrifice of the composition of the coal-derived gases.

1. Introduction

Gasification of coal is one of the most strategic pathways of coal processing. Market analysis of gasification technologies shows that the most popular are flow gasifiers, whose share is about 80% [1]. Flow technologies can be organized on the basis of both single-stage oxidizer and fuel feeding system, and using two-stage feeding. At that, in terms of the efficiency of conversion process, the lowest performance indicators are typical for single-stage gasifiers operating on coal-water mixture, while the highest indicators can be achieved in two-stage gasifiers with dry fuel feeding system.

The analysis of technical solutions used in new designs of gasifiers in terms of efficiency and economy of their application in solid-fuel combined cycle gas turbine units (CCGT) with integrated gasification has shown that the use of two-stage principle of the fuel conversion process is one of the upcoming trends in technology modernization. According to [2], the transition from single-stage process in the flow gasifier to two-stage process, even without optimization of the synthesis gas composition, can increase the efficiency of the CCGT by almost 1%.

The development of two-stage gasifiers with dry fuel feeding system is carried out according to two conceptual flow patterns: concurrent type with upward flow and combined countercurrent and concurrent flow pattern. The EAGLE-type two-stage gasifier, developed in the frameworks of the Japanese project "Coal Energy Application for Gas, Liquid and Electricity" (EAGLE) [3] is one of the original technical solutions based on a combined counter-current and concurrent flow pattern. In this paper, on the basis of numerical studies, using the Kuznetsk coal as a fuel, we examine the influence of several operating parameters of the EAGLE gasifier on the heat and mass transfer parameters in the gasification chamber as well as the efficiency of the gasification process.

2 Problem statement and research methods

The operational principle of the EAGLE gasifiers is based on a hydrodynamic flow separation providing a combined countercurrent and concurrent flow pattern (Fig.1). One advantage of this solution is reducing the required height of the reaction zone, while increasing the residence time of coal particles in the reactor. One flow, with the oxygen to coal ratio close to stoichiometric value, is delivered to the lower part of the gasification chamber. While combusting, it creates the necessary temperatures for efficient proceeding of the gasification reactions. The second flow, with the lack of air, is delivered into an upper part of the chamber, where it interacts with the high temperature upflow of combustion products. Due to the lack of oxygen for complete combustion, the carbon residue transforms into gasification reaction products through the conversion process. In this work, the Kuznetsk coal was used as a gasifier fuel (Table 1). The estimated coal consumption is 1700 t/day. The dimensions of the gasification chamber are presented in Fig. 2. Gasification air flow was selected based on the assumption that the maximum excess air was 0.32. The pulverized-coal was supplied at a high concentration under pressure. Nitrogen was used as pulverized-coal carrier. Blast burners of the bottom tier were enriched with oxygen (O_2=25 %, vol.) due to fuel transportation in the form of high-density pulverized coal carried by nitrogen. The upper tier of burners is supplied with both air and steam at an amount of 0.137 kg of steam per kg of coal. Coal consumption in the lower tier of burners made up 25% of the total amount of coal fuel supplied to the chamber. The air temperature in the lower tier was 830°C, and the temperature of air-steam mixture in the upper tier was 900°C.

Table 1. Technical and elemental analysis of Kuznetsk coal.

W^a, %	A^d, %	V^d, %	V^{daf}, %	C^{daf}, %	H^{daf}, %	N^{daf}, %	S^{daf}, %	O^{daf}, %	Q_s^{daf}, kc/kg
5.4	22.3	34.7	44.7	75.57	5.66	1.78	0.55	16.44	7086

For the numerical simulation of turbulent flow of an incompressible liquid we used the Reynolds equations taking into account the interfacial interaction. The Reynolds equations were closed using the standard two-parameter k-ε turbulence model. For modeling the wall boundary conditions we used the wall-functions method. The solution to the equation of radiant energy transport is based on the P1 approximation method of spherical harmonics for a gray two-phase two-temperature medium. The gas absorption coefficients are calculated according to the gray gases sum model, particles absorption and scattering coefficients are determined by the approximation of optically large particles. In the present work, to describe the particles motion we used the Lagrange method. Accounting for the flow turbulence in the particle motion is produced by the introduction of random fluctuations of the gas velocity into the particle motion equation. The calculation of chemical kinetics of gaseous fuel combustion is based on the use of global irreversible reactions between the combustibles and the oxidant. The rate of reactants combustion R_{vol}, including volatiles, is determined according to the reactive capacity and concentration of fuel and oxidizer, as well as the rate of turbulent mixing of fuel and oxidant. This model represents the combination of kinetic combustion model of the gas components with the eddy break-up model. The coal particle burning process was represented as the following consecutive steps: evaporation of moisture from the fuel, devolatilization and the combustion of the volatile components, and the combustion of the coke residue. Yield of volatiles is considered in the single-component approximation in the form of a $C_xH_yO_z$ substance. To calculate the rate of devolatilization we used single-stage kinetic model with constants given in Table 2. The combustion rate of coke residue was calculated in accordance with the provisions of the classical diffusion-kinetic theory. The specific reaction rates for the oxidation of the coke residue are given in Table 2. To describe gasification processes, we included into the mathematical model the reactions of steam-air conversion of coal. Reactions and kinetic constants are presented in Table 2.

The conservation equations for the gas phase are written in the form of a generalized conservation law in a control volume. Thus, finite-difference analog of the equation is written for the concerned volume. For calculation of diffusion fluxes on the faces of the control volume we used the central-difference scheme with second-order accuracy. When approximating convective terms, we used the second-order accuracy scheme with the differences against the flow. To correlate the velocity field and pressure we used SIMPLE-C procedure. Source terms that take into account the effect of dispersed phase on the carrier flow, are formed using the Particle-Source-In-Cell (PSI-CELL) method.

The proposed model and solution methods were previously tested for solving problems of pulverized coal combustion and gasification [4-8] and showed a satisfactory agreement with the experimental data on the basic process parameters in the combustion chamber.

Table 2. Specific reaction rates of combustion and gasification.

Reaction	Ks = A exp(-E/RT)		References
	m/s	J/mol	
1. $C + O2 \rightarrow CO + CO2$	$3.3 \cdot 10^4$	135756	[9]
2. $C + H2O \rightarrow CO + H2$	$1.6 \cdot 10^4$	181427	[10]
3. $C + CO2 \rightarrow 2CO$	$3.5 \cdot 10^4$	140365	[11]

3 Results and discussion

When carrying out computational studies, we have examined several options of the two-stage gasification process. Thus, for comparative analysis we considered the influence of the inclination angle of the upper tier burners (Figs. 3, 4) in the horizontal (angle α) and vertical (angle β) planes on heat and mass transfer processes in the chamber, as well as on the gases composition at the outlet. Initial data are presented in Table 3.

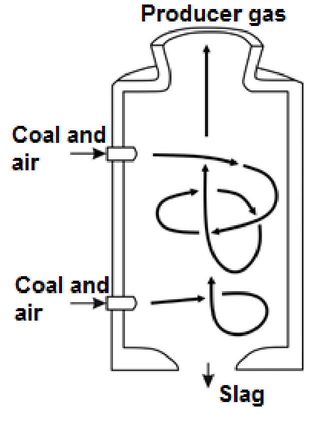


Figure 1. EAGLE gasifier

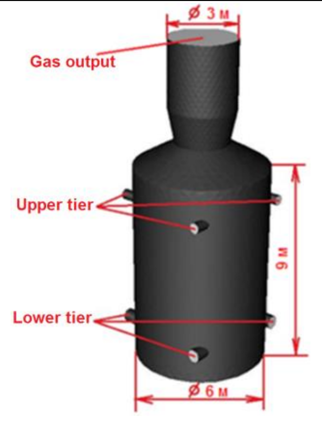


Figure 2. Feeding diagram and gasifier dimensions at a flow rate of 1700 t/h

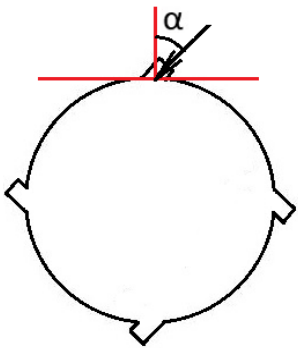


Figure 3. Inclination angle of burners in the horizontal plane of the upper tier

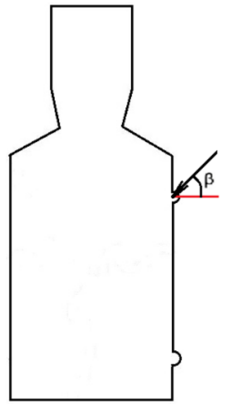


Figure 4. Inclination angle of burners in the vertical plane of the upper tier

Table 3. Gasification process options in the chamber.

Option	1	2	3
Inclination angle of upper burners α, °	30	45	60
Inclination angle of upper burners β, °	15	15	15
Inclination angle of bottom burners α, °	45	45	45
Inclination angle of bottom burners β, °	0	0	0

Figure 5 shows the calculations results presented in the form of the temperature field in the central section of the gasification chamber at different injection angles of pulverized coal and air-steam mixture into the upper tier of the burners. It is obvious that there is a significant influence of coal burners tilt in the horizontal plane on heat and mass transfer processes in the combustion chamber. Thus, the reduction of the inclination angle leads to a reduction in the high temperature region in the combustion chamber. This is due to the difference of the upward flow velocity in the center of the combustion chamber. In Fig. 6 we can see that the upward flow velocity in the center of the chamber at a height of H=2.5 m for the case of α=30° is 12 m/s, while for the rest options the velocity ranges from 5 to 7 m/s. Comparison of axial velocity profiles across the chamber at a height of H=2.5 m shows that at the angle of α=30° the downward gas flow along the chamber walls is less intense as compared to the angles α equal to 45 and 60°. At heights of H=5 and 6.5 m, we observed the alignment of the axial velocity profiles for all options. The temperature distribution along the height of the chamber is characterized by symmetry with respect to the axis, while temperature in the chamber increases with reducing the flow injection angle α. This is explained by more intense flow of descending gas and fuel from the upper tier of burners at increased injection angle α that contributes to better mixing with the pulverized coal combustion products of lower tier burners, as well as more intense endothermic gasification reactions with the evolution of gasification products in the form of CO and H_2 (Fig. 6). Temperatures and gas compositions at the exit of the chamber are approximately the same for all options (Table 4). The increase in the angle α allows intensifying the two-stage gasification process and makes it possible to reduce the height of the chamber without sacrifice of the coal-derived gas composition.

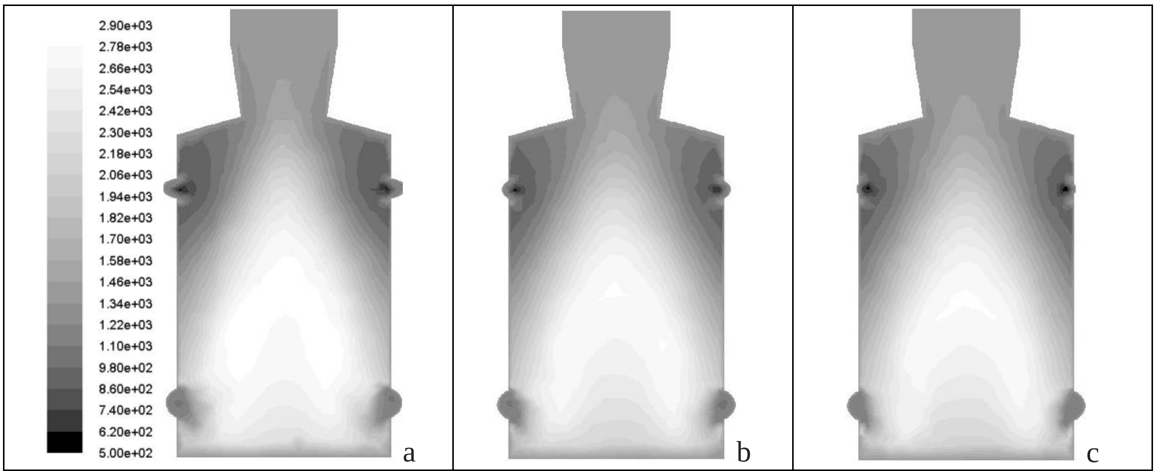
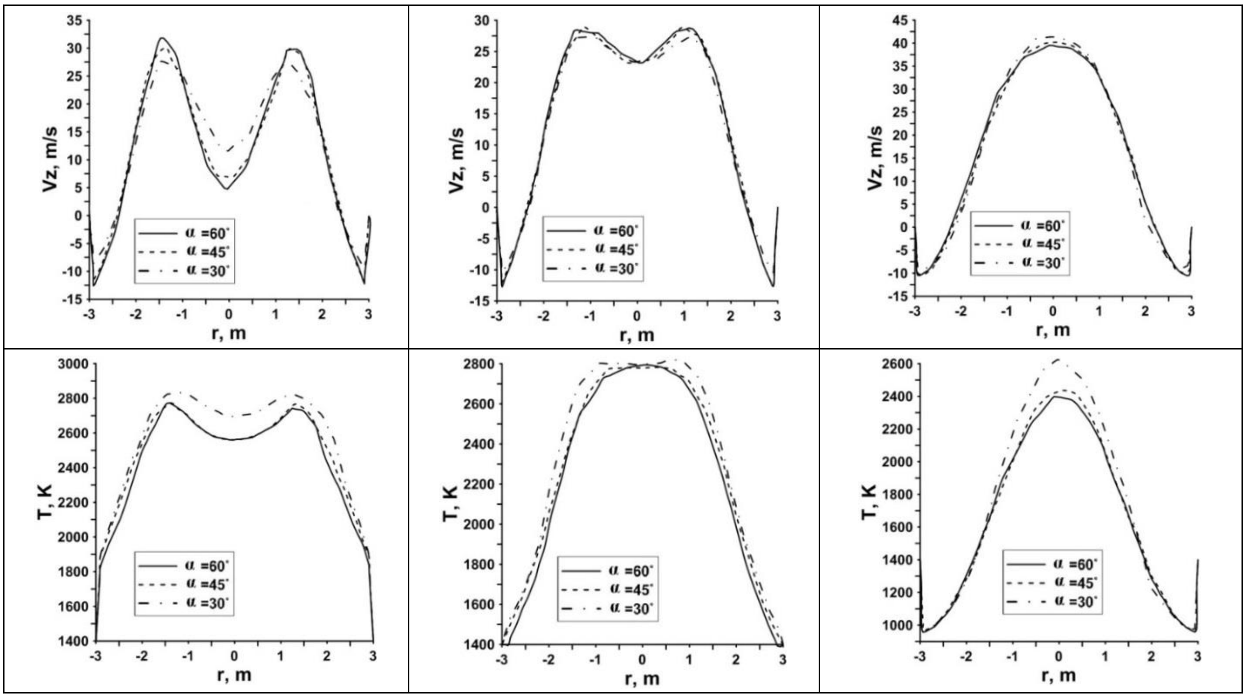
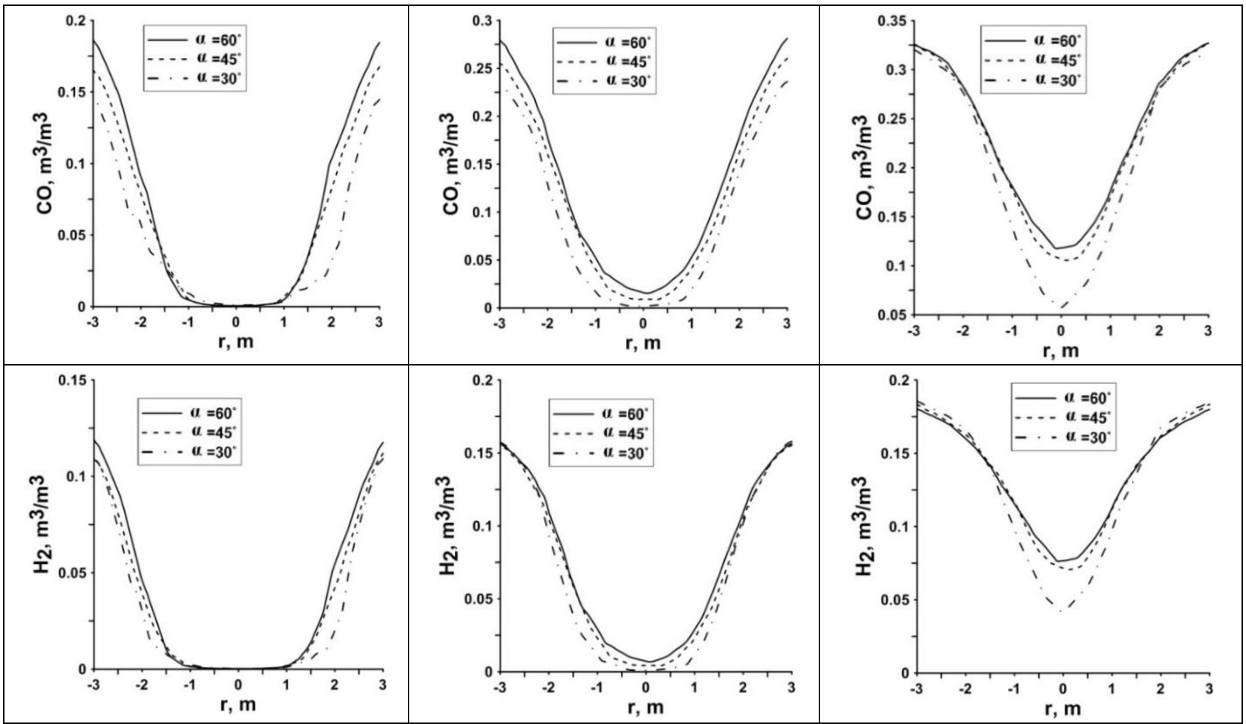


Figure 5. Temperature distribution in the central section of the chamber, K.





H=2.5 m	H=4.5 m	H=6.5 m

Figure 6. Radial distribution of axial velocity, temperature, and volumetric concentration of carbon monoxide and hydrogen over the chamber height.

The results of computational studies are presented in Table 9 in terms of the coal-derived gas composition at the outlet of the chamber. Comparative analysis shows that increasing of angle α leads to increase of chemical efficiency from 84.7% to 86%.

We have studied also the effect of steam on the pulverized-coal gasification process. As in the above considered simulations, the steam with a temperature of 900°C was supplied to the upper burners. Steam flow rate was ranged from 0 to 0.5 kg of steam per kg of coal. The simulations were performed for option #3 with angles $\alpha = 60°$ and $\beta = 15°$. The results of computational studies are presented in Table 5. We can see that the increase in the amount of superheated steam leads to a change in the composition of the coal-derived gas at the outlet of the gasification chamber. Thus, the proportion of CO reduces while the proportion of H_2 increases. Increasing the proportion of H_2 leads to increase in chemical efficiency of the process to 87% at steam flow rate equal to 0.5 kg steam per kg of coal.

Table 4. The composition of the coal-derived gas at the outlet of the chamber.

Option No.	1	2	3
CO, %°	27.87	27.91	28.5
H_2, %°	16.75	16.73	16.6
CO_2, %°	4.7	4.65	4.51
H_2O, %°	2.06	2.1	2.21
CH_4, %°	2.33	2.39	2.3
N_2, %	46.29	46.22	45.88
Gas temperature at the outlet, K	1367	1377	1382
Chemical efficiency	84.7	85	86

Table 5. The composition of the coal-derived gas at the exit of the chamber depending on the amount of injected steam.

Amount of steam, kg of steam / kg of coal	Chemical efficiency, %	$CO+H_2+CH_4$, vol. %	Gas temperature at the outlet, K
0.5	87	20.73+20+0.9	1343
0.268	86	25.7+19.3+1.4	1372
0.137	86	28.5+16.6+2.3	1382
0.089	85	29.8+16+2.3	1386
0.045	85	31.1+14.6+2.65	1398
0	83	31.5+13.8+2.8	1414

Conclusion

Numerical studies of advanced two-stage flow gasifier have been carried out for Kuznetsk coal gasification, based on hydrodynamic flow separation with the implementation of a combined counter-current and concurrent flow pattern.

It is shown that the increase of the inclination angle of the burners of the upper tier in a horizontal plane leads to a decrease in the velocity of the upward central flow, as well as to reduction of the height of the high-temperature combustion zone that enables decreasing the height of the chamber without reducing the chemical efficiency of the gasification process.

Moreover, computational studies on the influence of high-temperature steam on the pulverized-coal gasification process were carried out. It was revealed that the increase of steam supply from 0 to 0.5 kg of steam per kg of coal at a temperature of 1173 K leads to an increase in chemical efficiency of the gasification process from 83 to 87%, as well as lowers the temperature at the outlet of the gasification chamber from 1414 to 1343 K.

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